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13. ABSTRACT *(Maximum 200 words)*

We have fulfilled our contract obligations completely by doing theoretical research on electron-phonon interaction and transport properties in submicron semiconductor structures with the emphasis on ultrafast processes and many-body effects. Fifty-five papers have been published based on our research during the contract period.

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ELECTRON-PHONON INTERACTION, TRANSPORT AND ULTRAFAST PROCESSES IN SEMICONDUCTOR MICROSTRUCTURES

FINAL REPORT

1989-1992

Sankar Das Sarma

Professor of Physics

August 14, 1992

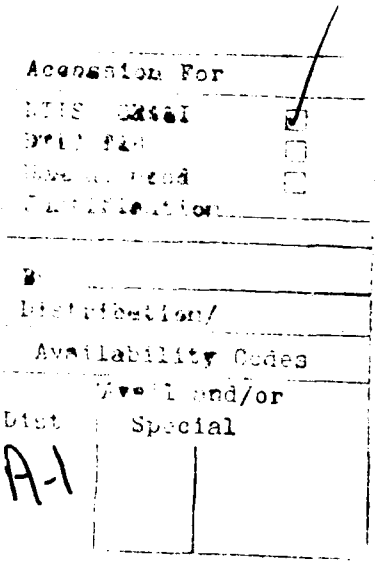
U.S. Army Research Office

Contract No. DAAL03-89-K-0026

ARO Proposal Number 26278-EL

University of Maryland

College Park, MD 20742



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Final Report on ARO Contract Number DAAL03-89-K-0026

During the last six years we have published (or, had accepted for publication) one hundred (100) papers in refereed journals (including many invited papers in international conferences, invited reviews and book chapters) under ARO support. We have had sixty (60) refereed publications under ARO sponsorship so far during the current three-year contract period. In addition, there are currently about half a dozen papers which have either been submitted for publication (or, will soon be submitted). A publication list is provided at the end of this section.

During the current three year contract period we have had thirty (30) invited papers, session chairmanship, etc. in international conferences for work done under ARO sponsorship. In addition, we gave a large number (~20) of invited seminars, colloquia and lectures at various universities and research laboratories on our research. We made over forty (40) scientific presentations at international conferences (including APS March meetings) on work related to the current ARO contract. Among our invited papers are two at the Hot Electron Conferences, two at the APS March meetings, two at NATO school on nanostructures, one at the IEEE meeting, several at SPIE meetings, and, a number of invited talks at specialized workshops (held by DoD agencies such as ONR) on nanostructures and ultrafast processes. We contributed an invited chapter[9] on many-body effects to the recent book of reviews[4] on hot carrier physics and applications in nanostructures which is edited by J. Shah of AT&T and published by the Academic Press. We published ten (10) invited reviews on work done under ARO sponsorship. Of these, four invited reviews are book chapters in recently published books on nanostructures.

Three postdoctoral research associates partially supported by our ARO contract have gone on to obtain tenure-track assistant professorship positions in physics departments of major research universities. The five graduate students who did their PhD research under the sponsorship of this contract have all gone on to excellent postdoctoral positions. We provide a personnel list at the end of this

section.

The PI, Sankar Das Sarma, has been awarded a Distinguished Research Fellowship for nanostructure research by the Graduate School of the University of Maryland for the 1991-92 academic year. (This is the highest research honor awarded by the university.) He is a member of the Organizing Committee for 10th International Conference on Electronic Properties of Two Dimensional Systems (to be held in Newport, Rhode Island in June of 1993), which is considered to be the premier conference on the physics of nanostructures. Das Sarma has been awarded the Gordon Godfrey Bequest Visiting Professorship by the University of New South Wales, Australia where he will give a series of lectures on the physics of nanostructures during the summer of 1992. Earlier, in 1988-89 he was awarded a Royal Society Visiting Professorship and Fellowship to the Cavendish Laboratory (Cambridge University) by the British Royal Society. In 1988, Das Sarma was also one of the ten scientists invited to the Soviet Union by the Soviet Academy of Sciences as a part of US - Soviet bilateral scientific exchange program in low-dimensional electron systems.

Following is a very brief summary of some of the highlights of our research accomplishment under the current ARO support.

1. Many-body effects in hot electron relaxation.

Our detailed theory, within the electron temperature and the hot phonon model, essentially completely solves the problem of picosecond hot electron relaxation via LO-phonon emission in two dimensional nanostructures. Our theory includes quantum subband structure, quantum degeneracy, dynamical screening, plasmon-phonon coupling, quasiparticle-phonon coupling induced phonon self-energy correction, slab and interface phonon modes, and, hot phonon bottleneck effect. We get good agreement with the available experimental results and explain the low temperature "missing loss" mechanism as that due to quasiparticle-phonon coupling.

2. Inelastic scattering in ballistic transistors

We have developed a many-body theory, which includes Coulomb electron-electron and Fröhlich electron-phonon interactions on an equal footing for the first time, for inelastic processes in ballistic hot electron transistors (e.g., THETA devices), calculating energy-, doping density-, and, temperature- dependence of the ballistic electron inelastic mean free path in the base region. Our theory considers both two dimensional and three dimensional systems, corresponding respectively to lateral and vertical motion through the base region.

3. Band gap and effective mass renormalization

We have obtained the exchange-correlation induced band gap and effective mass renormalization in two and three dimensional semiconductor structures, including both electron-electron and electron-phonon interaction effects. Our results are in excellent agreement with the available experimental data.

4. Scattering effects on resonant tunneling in nanostructures

We developed a microscopic theory for the impurity scattering effect on the resonant tunneling current through a double-barrier-single-quantum-well structure, showing that disorder can produce conductance fluctuation- and weak localization-type structure on the tunneling current spectra. Our microscopic theory also provides a justification for the Breit-Wigner type phenomenological formula used in the literature.

5. Vertical miniband transport in superlattices

We have developed a detailed Bloch type theory, based on the Kubo formula, for vertical transport through minibands in superlattices. Our theory explains a number of puzzling experimental results in superlattice miniband transport.

6. Electronic structure of nanostructures

We have developed a self-consistent theory (including exchange-correlation effects) for calculating the electronic structure of parabolic semiconductor quantum wells, both with and without an external magnetic field. Our numerical

results are in good agreement with spectroscopic and transport data. We also developed a theory for the shallow impurity donor levels in GaAs quantum wells by exactly solving the Schrödinger's equation in the whole system (i.e., including the barrier).

7. Transport properties of high electron mobility nanostructures

We have developed a comprehensive theory for the electronic mobility of a high mobility modulation-doped GaAs heterojunction by solving the Boltzmann integral equation exactly numerically through an iterative procedure. Our theory includes all relevant phonon scattering processes. Our calculation includes finite temperature and dynamical screening effects, and, shows that the highest achievable mobility in a GaAs heterojunction to be about 4 x 10^6 $cm^2/v/s$ at 10 K and about 4 x 10^7 $cm^2/v/s$ at 1 K. We also explained the recently observed density dependent maximum in the temperature dependence of low temperature mobility as a competition between screening and deformation potential matrix element effect.

8. Optical properties of quantum dots and wires

We have carried out some preliminary calculations of optical properties of quantum wires and dots. Our theory for the quantum wire collective plasmon spectra has recently been verified by a Raman scattering experiment.

9. Inelastic processes in quantum wires

We have shown that, due to very strict restrictions imposed by energy-momentum conservation in one dimension, inelastic scattering is highly constrained in quantum wires, leading to a very sharp plasmon emission threshold. This phenomenon should lead to a strong negative differential resistance and we have proposed a device based on this (Appendix A).

10. Electron-phonon coupling in quantum wires

We have developed a detailed theory for electron-phonon coupling in semiconductor quantum wires, including slab phonon and dynamical screening effects. We have applied our theory to the carrier energy relaxation problem in quantum wires (Appendix B).

In the following we provide a list of our publications (during the last three years) under the current ARO support and some other relevant information.

Publications (under the current ARO contract)

1. Band-Gap Renormalization in Quasi-Two Dimensional Systems by Many-Body Electron-Electron and Electron-Phonon Interactions (S. Das Sarma, R. Jalabert, and S. R. E. Yang), Phys. Rev. B (Rapid Commun.) 39, 5516 (1989).

2. Many-Polaron Interaction Effects in Two Dimensional Systems (R. Jalabert and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 39, 5542 (1989).

3. Role of Discrete Slab Phonons in Carrier Relaxation in Semiconductor Quantum Wells (J. K. Jain and S. Das Sarma), Phys. Rev. Lett. 62, 2305 (1989).

4. Calculated Shallow Donor-Level Binding Energies in GaAs-$A\ell_xGa_{1-x}As$ Quantum Wells (M. Stopa and S. Das Sarma), Phys. Rev. B 40, 8466 (1989).

5. Calculated Heat Capacity and Magnetization of Two Dimensional Electron Systems (Q. Li, X. C. Xie, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 1381 (1989).

6. Quantum Conduction in Narrow Constrictions (S. He and S. Das Sarma), Phys. Rev. B 40, 3379 (1989).

7. Elastic Scattering in Resonant Tunneling Systems (H. A. Fertig and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 7410 (1989).

8. Quasiparticle Properties of a Coupled Two Dimensional Electron-Phonon System (R. Jalabert and S. Das Sarma), Phys. Rev. B 40, 9723 (1989).

9. Parabolic Quantum Well Self-Consistent Electronic Structure in a Longitudinal Magnetic Field: Subband Depopulation (M. Stopa and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 40, 10048 (1989).

10. A Many-Body Theory of Energy Relaxation by an Excited Electron Gas through Optical Phonon Emission (S. Das Sarma, J. K. Jain, and R. Jalabert), Phys. Rev. B 41, 3561 (1990).

11. Elastic Scattering Effects on Resonant Tunneling in Double Barrier Quantum Well Structures (H. Fertig, S. He, and S. Das Sarma), Phys. Rev. B 41, 3596 (1990).

12. Inelastic Scattering in a Doped Polar Semiconductor (R. Jalabert and S. Das Sarma), Phys. Rev. B 41, 3651 (1990).

13. Localization, Mobility Edges, and Metal-Insulator Transition in a Class of One Dimensional Slowly Varying Deterministic Potentials (S. Das Sarma, S. He, and X. C. Xie), Phys. Rev. B 41, 5544 (1990).

14. Band Gap Renormalization in Semiconductor Quantum Wells (S. Das Sarma, R. Jalabert, and S. R. E. Yang), Phys. Rev. B 41, 8288 (1990).

15. Re-Entrant Localization and a Mobility Gap in Superlattice Minibands (H. A. Fertig and S. Das Sarma), Phys. Rev. B 42, 1448 (1990).

16. Temperature Dependence of the Low Temperature Mobility in Ultrapure $Al_xGa_{1-x}As$/GaAs Heterojunctions: Acoustic Phonon Scattering (T. Kawamura and S. Das Sarma), Phys. Rev. B 42, 3725 (1990).

17. Finite Size Studies of Semion Systems (X. C. Xie, Song He, and S. Das Sarma), Phys. Rev. Lett. 65, 649 (1990).

18. Low Temperature Energy Relaxation in GaAs/$Al_xGa_{1-x}As$ Heterojunctions (T. Kawamura, S. Das Sarma, R. Jalabert, and J. K. Jain), Phys. Rev. B (Rapid Commun.) 42, 5407 (1990).

19. Cyclotron Effective Mass Studies of Wide Parabolic Quantum Wells (K. Karrai, M. Stopa, X. Ying, H. D. Drew, S. Das Sarma, and M. Shayegan), Phys. Rev. B (Rapid Commun.) 42, 9732 (1990).

20. Collective Modes in Layered Superconductors (H. A. Fertig and S. Das Sarma), Phys. Rev. Lett. 65, 1482 (1990).

21. Density of States and Thermodynamic Properties of a Two Dimensional Electron Gas in a Strong External Magnetic Field (X. C. Xie, Q. Li, and S. Das Sarma), Phys. Rev. B 42, 7132 (1990).

22. Destruction of Fractional Quantum Hall Effect in Thick Systems (S. He, F. C. Zhang, X. C. Xie, and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 42, 11376 (1990).

23. Theory of Pairing in the Anyon Model (X. C. Xie, H. A. Fertig, and S. Das Sarma), Modern Phys. Lett. 4, 1265 (1990).

24. The Electrodynamic Response of a Harmonic Atom in an External Magnetic Field (Q. P. Li, K. Karraï, S. K. Yip, S. Das Sarma, and H. D. Drew), Phys. Rev. B 43, 5151 (1991).

25. Quantum Hall Effect in Double Quantum Well Systems (S. He, X. C. Xie, S. Das Sarma, F. C. Zhang), Phys. Rev. B (Rapid Commun.) 43, 9339 (1991).

26. Fermion-Boson Mapping and Off-Diagonal-Long-Range-Order in Fractional Quantum Hall Effect (X. C. Xie, S. He, and S. Das Sarma), Phys. Rev. Lett. 66, 389 (1991).

27. Collective Excitations and Mode Coupling in Layered Superconductors (H. A. Fertig and S. Das Sarma), Phys. Rev. B 44, 4480 (1991).

28. Many-Body Vertex Corrections on Quasiparticle Properties of Two Dimensional Electron Systems (I. K. Marmorkos and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 44, 3451 (1991).

29. Inelastic Scattering in Doped Polar Semiconductors at Finite Temperatures (Y. K. Hu and S. Das Sarma), Phys. Rev. B 44, 8319 (1991).

30. Quantum Theory of Infrared Absorption in a Grating-Coupled Two Dimensional Electron Gas (D. Z. Liu and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 44, 9122 (1991).

31. On the Nature of Coupled-Mode Contributions to Hot-Electron Relaxation in Semiconductors (S. Das Sarma and V. Korenman), Phys. Rev. Lett. 67, 2916 (1991).

32. Phonon Scattering Limited Electron Mobilities in $Al_xGa_{1-x}As$/GaAs Heterojunctions (T. Kawamura and S. Das Sarma), Phys. Rev. B 45, 3612 (1992).

33. Hot Electron Relaxation in Semiconductor Quantum Wires: Bulk LO-Phonon Emission (V. Campos and S. Das Sarma), Phys. Rev. B (Rapid Commun.) 45, 3898 (1992).

34. Electronic Structure, Density Scaling, and, Optical Properties of Parabolic and Square Quantum Wells (M. P. Stopa and S. Das Sarma), Phys. Rev. B.

35. Many-Body Properties of a Quasi-One Dimensional Semiconductor Quantum Wire (Ben Hu and S. Das Sarma), Phys. Rev. Lett. 68, 1750 (1992).

36. Magnetoplasmon Excitation Spectrum for Integral Filling Factors in a Two-Dimensional Electron System, Phys. Rev. B.

37. Effect of Interplane Coupling on Anyon Superconductivity (H. A. Fertig, S. He and S. Das Sarma,) Phys. Rev. Lett.

38. Theory of Ballistic Electron Transport Through Quantized Constrictions (S. He and S. Das Sarma), Solid State Elec. 32, 1695 (1989).

39. Inelastic Scattering Effects on Carrier Relaxation in Quantum Well-Based Hot Electron Structures (R. Jalabert and S. Das Sarma), Solid State Elec. 32, 1259 (1989).

40. Many-Body Effects in GaAs-based Two Dimensional Electron Systems (R. Jalabert and S. Das Sarma), Surf. Sci. 229, 405 (1990).

41. Optical and Transport Properties of One Dimensional Quantum Wire Structures (S. Das Sarma, S. He, and Q. Li), Surf. Sci. 229, 264 (1990).

42. Low Temperature Transport and Power Loss in Heterojunctions (T. Kawamura and S. Das Sarma), Proceedings of 20th International Conference on the Physics of Semiconductor (Thessaloniki, Greece, August 1990), p. 1633 (World Scientific, 1990).

43. Localization Properties of a Superlattice Miniband (H. A. Fertig and S. Das Sarma), Proceedings of 20th ICPS, p. 1246 (World Scientific, 1990).

44. Fractional Quantum Hall Effect in Thick Layers and Double Quantum Well Systems (S. He, X. C. Xie and S. Das Sarma), Surf. Sci. 263, 87 (1992).

45. Inelastic Scattering of Hot Electrons in Doped Polar Semiconductors at Finite Temperatures (B. Hu and S. Das Sarma), Semiconductor Sci. & Tech.

46. Behavior of Electrons at Soft Edges in the Fractional Quantum Hall and Wigner Crystal States (H. A. Fertig and S. Das Sarma), Surf. Sci. 263, 60 (1992).

47. Hot Electron Relaxation in Polar Semiconductors (S. Das Sarma, J. K. Jain, and R. Jalabert), Solid State Electronics, 31, 695 (1988). Invited Review.

48. Relaxation of Ultrafast Electrons in Semiconductors: Many-Body Effects (S. Das Sarma, J. K. Jain, and R. Jalabert), SPIE Proc. 942, 47 (1988). Invited Review.

49. Theory of Electronic Density of States of a Two Dimensional Disordered System in the Presence of a Strong Magnetic Field (S. Das Sarma and X. C. Xie), J. App. Phys. 54, 5465 (1988). Invited Review.

50. Confined Phonon Modes and Hot Electron Energy Relaxation in Semiconductor Microstructures (S. Das Sarma, V. B. Campos, M. A. Stroscio and K. W. Kim), Semiconductor Sci. & Tech. Invited Review.

51. Collective Modes of Semion Systems (X. C. Xie, Song He and S. Das Sarma), Int. J. Mod. Phys. B 5, 1607 (1991). Invited Review.

52. Elementary Excitations in Low Dimensional Semiconductor Structures (S. Das Sarma), p. 499 in the book: "Light Scattering in Semiconductor Structures and Superlattices" (Ed." D. J. Lockwood and J. F. Young, Plenum, 1991). Invited Review.

53. Theory of Electronic Transport in Low Dimensional Semiconductor Microstructures (S. Das Sarma), p. 261 in the book "Condensed Systems of Low Dimensionalities" (Ed.: J. Beeby, Plenum, 1991) Invited Review.

54. Quantum Many-Body Aspects of Hot Carrier Relaxation in Semiconductor Microstructures (S. Das Sarma), Ch. II.2 in the book "Hot Carriers in Semiconductor Microstructures," (Ed.: J. Shah, Academic Press, 1991). Invited Review.

55. Density of States of a Two-Dimensional Electron Gas in High Magnetic Fields (S. Das Sarma), to appear in the book "High Magnetic Fields in Semiconductors," (Ed.: G. Landwehr, Springer-Verlag, 1991). Invited Review.

Invited Talks at International Conferences (the last 3 years)

1. Chair, Session on Quantum Constrictions and Narrow Wires, International Symposium on Nanostructure Physics and Fabrication (Texas, March 1989).

2. Chair, Session on Quantum Hall Effect, APS March Meeting (St. Louis, March 1989).

3. Chair, Session on Many-Body Effects, APS March Meeting (St. Louis, March 1989).

4. Invited Speaker, Kathmandu Summer School on Theoretical Physics (Nepal, Summer 1989); "Unusual Solutions to the Usual Schrödinger's Equation."

5. Invited Talk, International Symposium on Surface Waves in Solids and Layered Structures (Bulgaria, Summer 1989); "Collective Excitations in Structured Low Dimensional Systems."

6. Invited Talk, 36th Annual AVS Symposium (Boston, October 1989) "Non-equilibrium Crystal Growth".

7. Invited Speaker, 5th International Workshop on Physics of Semiconductor Devices (New Delhi, December 1989).

8. Invited Plenary Lecturer, Brazilian Summer School on Low Dimensional Systems (Sao Carlos, Brazil, February 1990).

9. Invited Speaker, NATO Workshop on "Light Scattering in Semiconductors" (Canada, March 1990); "Excitations and Mode Coupling a Doped Polar System."

10. Chair, Related Phenomena Session, NATO Workshop on Light Scattering in Semiconductors (Canada, March 1990).

11. Chair, Session on Many-Body Theory, APS March Meeting (Anaheim, March 1990).

12. Chair, Session on Transport in Microstructures, APS March Meeting (Anaheim, March 1990).

13. Invited Speaker, NATO Workshop on "Transport in Microstructures" (Turkey, April 1990).

14. Chair, Quantum Transport Session, Workshop on Computational Electronics (Univ. of Illinois, May 1990).

15. Invited Speaker, Winter School on Theoretical Physics (Brasilia, Brazil, July 1990).

16. Invited Speaker, International Conference on Application of High Magnetic Fields in Semiconductors (Würzburg, W. Germany, August 1990).

17. Invited Speaker, SPIE International Optoelectronics Conference (Aachen, W. Germany, October 1990).

18. Invited Review in "Hot Carriers in Semiconductor Microstructures," (Ed.: J. Shah, Academic Press 1990).

19. Workshop on Optical Properties of Mesoscopic Semiconductor Structures (Snowbird, Utah, April 1991).

20. Invited Talk, International Workshop on Computational Methods in Physics (Taormina, Italy, May 1991).

21. Invited Talk, Eighteenth IEEE International Conference on Plasma Science (Williamsburg, Virginia, June 1991).

22. Invited Lecture Series, International School on Many-Body Techniques in Condensed Matter Physics (Trieste, Italy, June 1991).

23. Invited Review, Seventh International Conference on Hot Carriers in Semiconductors (Nara, Japan, July 1991).

24. Invited Review, First International Symposium on Atomically Controlled Surfaces and Interfaces (Tokyo, Japan, November 1991).

25. Invited Lecture Series, Canadian Summer School in Theoretical Physics (London, Canada, August 1991).

26. Chair, First International Symposium on Atomically Controlled Surfaces & Interfaces (Tokyo, November 1991).

27. Invited Speaker, International Workshop on Disorder (Hyderabad, India, December 1991).

28. Invited Review, "Anyons in Condensed Matter Physics," Special Issue of Int. J. Mod. Phys. Nov. 1991, World Scientific.

29. Highlight Presentation, "MBE growth," 19th PCSI Conference (Death Valley, January 1992).

30. Invited Speaker, SPIE International Conference on Fast Optoelectronics (Somerset, New Jersey, March 1992).

31. Chair, SPIE International Conference on Ultrafast Phenomena (Somerset, March 1992).

32. Invited Talk, APS March Meeting (Indianapolis, March 1991); "Quantum Hall Effect in Double Quantum Well Systems".

33. Chair, Mesoscopic Systems, APS March Meeting (Indianapolis, March 1992).

34. Invited Visitor, Workshop on Quantum Phase Transitions, ITP, Univ. of California, Santa Barbara (Spring-Summer 1992).

35. Chair, One Dimensional Systems, APS March Meeting (March 1992).

36. Invited Talk, European Science Foundation Conference on Kinetics of Epitaxial Growth (Davos Platz, Switzerland, Summer, 1992).

Personnel (at least partially) supported by ARO (last 3 years)

Graduate students:

1) R. Jalabert (PhD 1989), IBM postdoctoral fellow at Yale University.

2) M. P. Stopa (PhD 1990), staff research scientist at NTT Basic Sciences Laboratory, Tokyo.

3) Song He (PhD 1991), postdoctoral research associate at the Theory Group, AT&T Bell Laboratory.

4) T. Kawamura (PhD 1991), postdoctoral research associate at the Coordinated Sciences Laboratory, University of Illinois, Urbana-Champaign.

5) I. K. Marmorkos (PhD 1991) research scientist at the Lorenz Theory Institute, University of Leiden, Netherlands.

Research associates:

1) J. K. Jain, currently a tenure-track assistant professor at the physics department of SUNY, Stony Brook.

2) X. C. Xie, currently a tenure-track assistant professor at the physics department of Oklahoma State University.

3) H. A. Fertig, currently a tenure-track assistant professor at the physics department of University of Kentucky.

4) Y. K. (Ben) Hu, currently at Maryland.